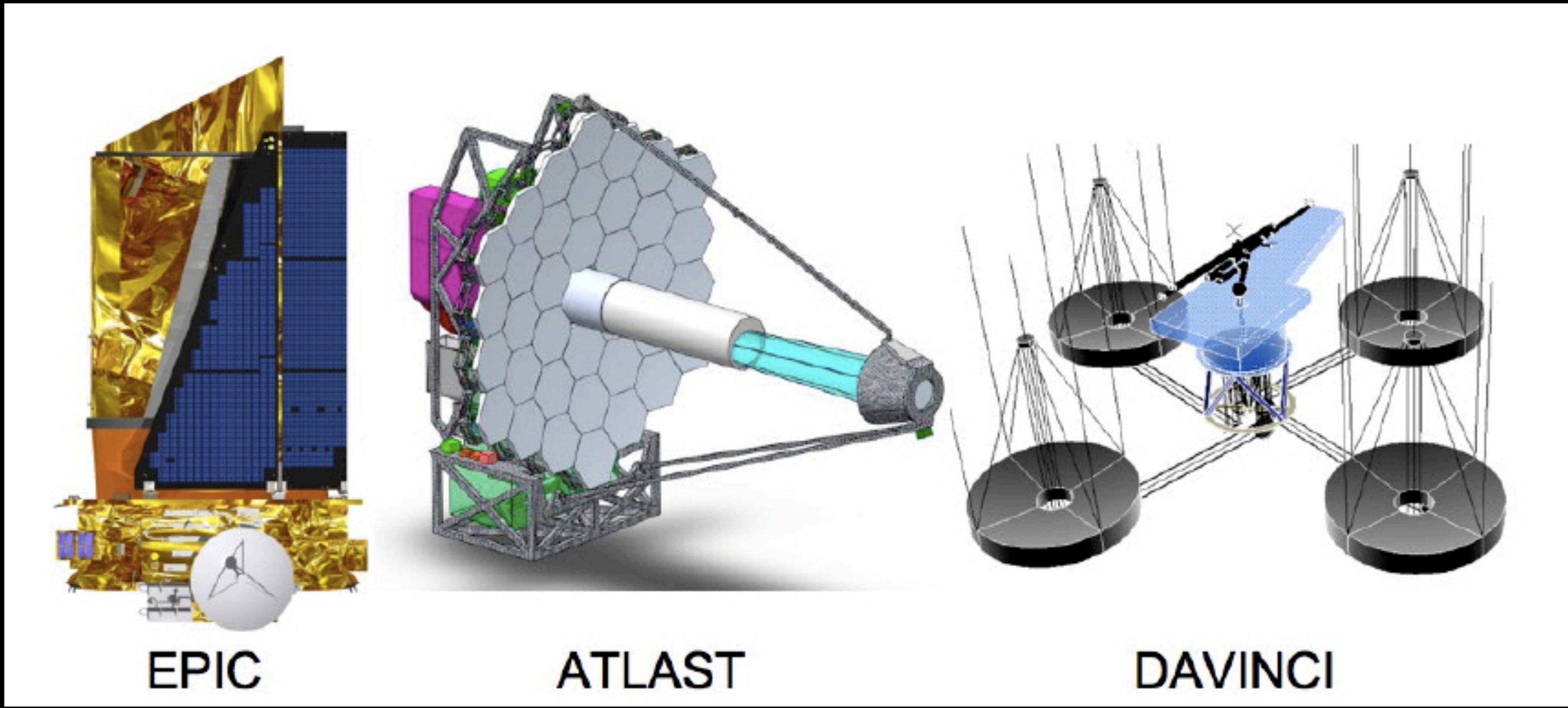
Visible Nuller Coronagraph Simulations

Bertrand Mennesson
Jet Propulsion Laboratory, California Institute of Technology
(presented by Jagmit Sandhu)

Visible Nuller Intrument is common to 3 separate NASA ASMC Coronagraph Studies:



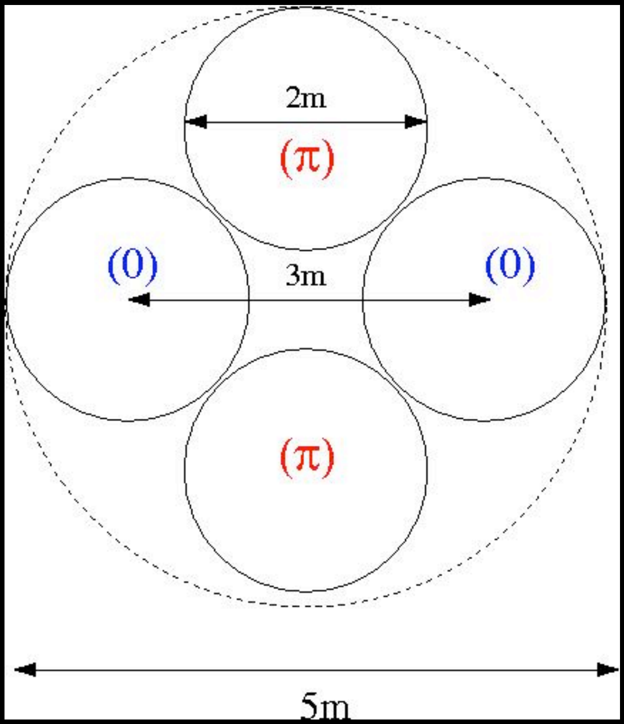
- ✓ EPIC : Extrasolar Planetary Imaging Coronagraph (Lyon, Clampin, Woodruff et al. 2010)
- ✓ ATLAST : Advanced Technology for Large aperture Space Telescope (Postman et al. 2010)
- ✓ DAVINCI : Diluted Aperture Visible Nulling Coronagraph Imager (Woodruff, Shao et al. 2010)

General Architecture Studied: 4 Beam Nulling

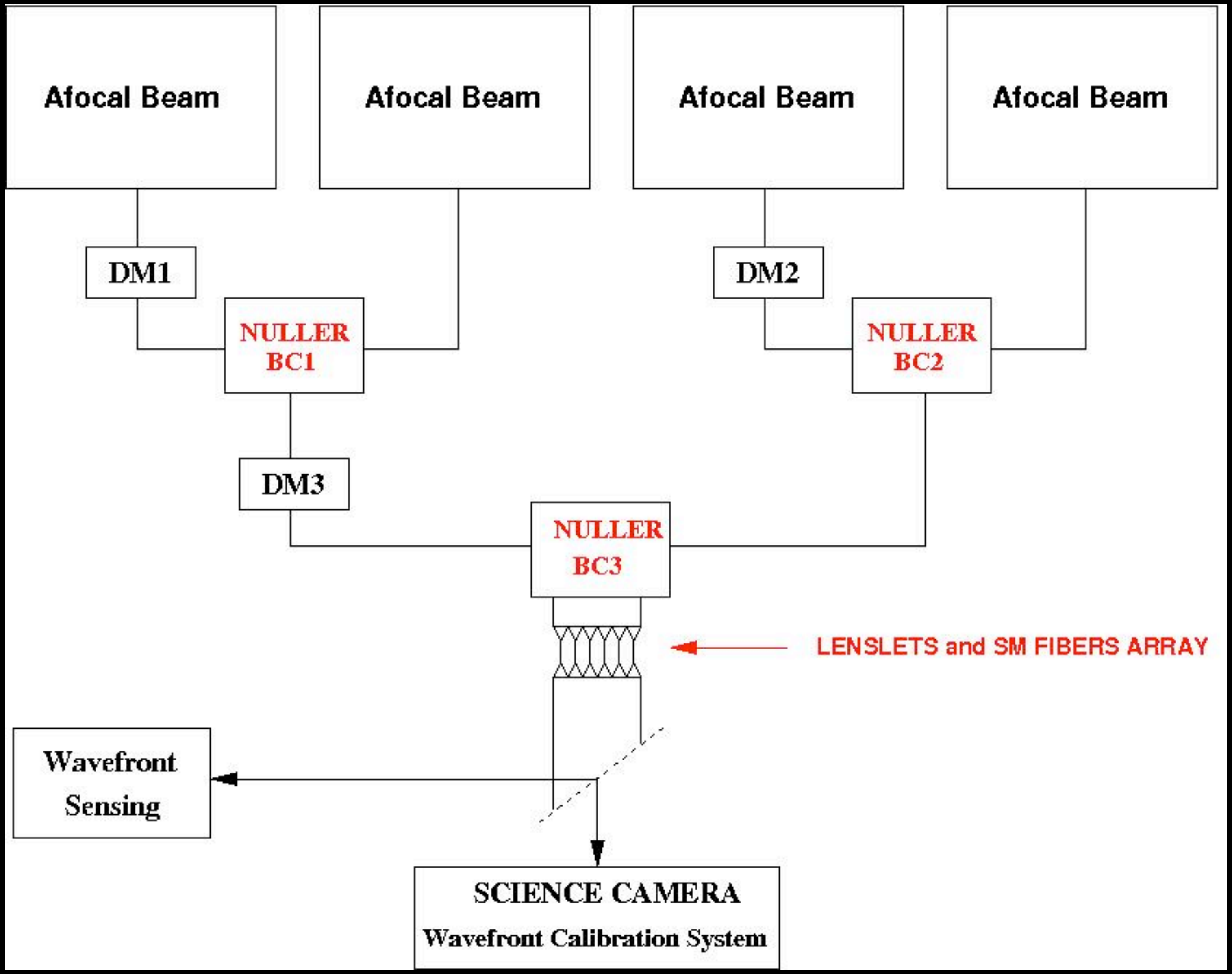
- ✓ Representative of all 3 ASMC studies (but assumes rigid body pointing)
- ✓ Can simulate arbitrary beam sizes and baseline lengths
- ✓ Simulates speckle fields in 4 x 20% BW filters centered at B,V, R, H
- ✓ Only V band results shown here

Used individual beam diameter D=2m, baseline B=3m and V band for simulations presented here:

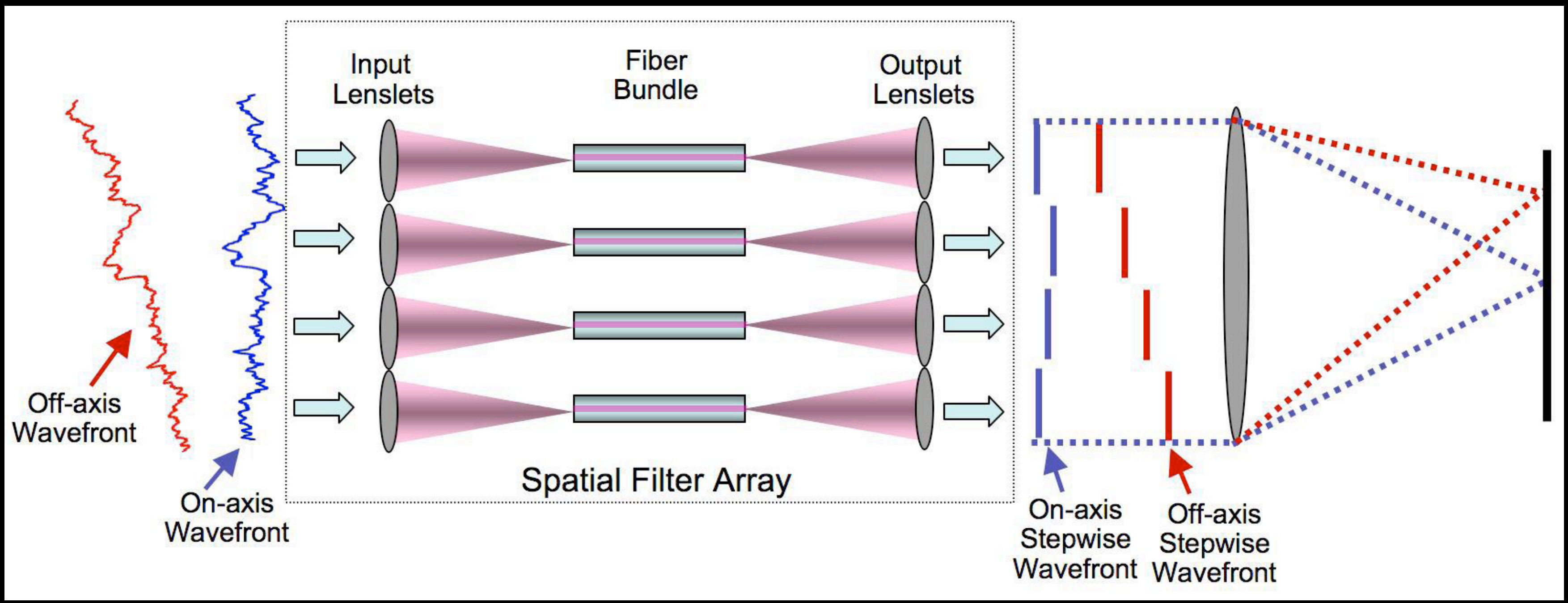
(In the case of a single telescope, the baseline B corresponds to the beam shear, which can be adjusted per star)



Instrument Block Diagram

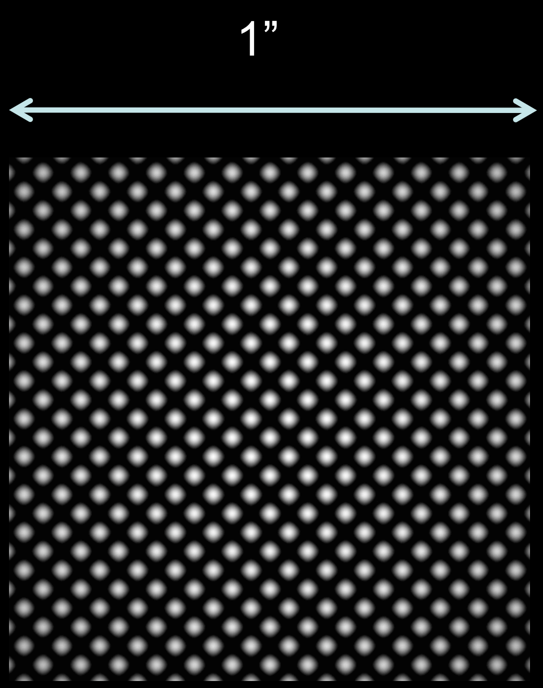


Zoom on SM Fiber Array

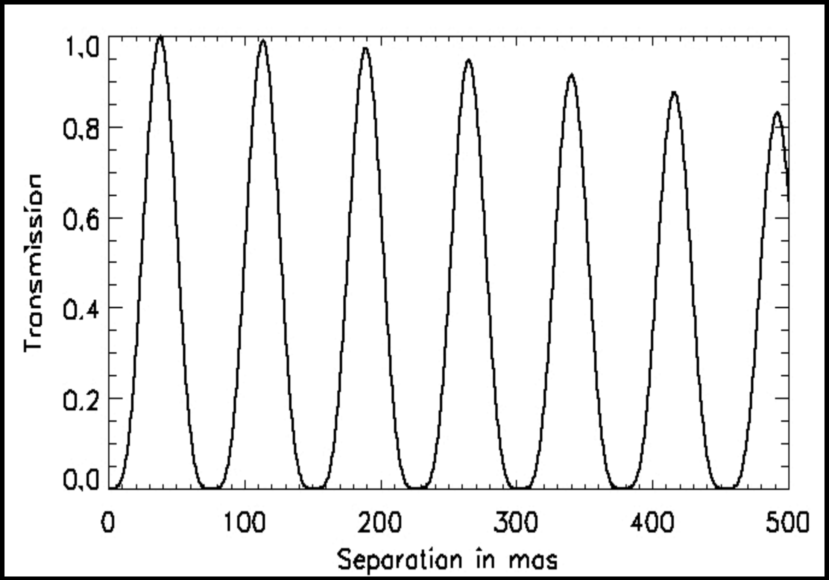


Simulations assume hexagonally shaped Array of 1027 SM Fibers
and hexagonally packed lenslets

Sky Transmission Pattern



Sky transmission pattern
(tapering due to SM fiber FOV)



Monochromatic transmission at 550nm along X axis
Half power point is $(2/\pi)\ \lambda/B$
That is 0.85 λ/D with D=4m (diameter adopted for Lyot and external occulter designs)

Simulations Principle and Building Blocks

Assumes science integration is made of many DM piston and tip-tilt corrections of finite duration, resulting in:

- ✓ Finite Wavefront Measurement SNR → Residual rms error on both amplitude and phase for each beam and for each fiber (spatial white noise floor)

Simulations Principle and Building Blocks

Assumes science integration is made of many DM piston and tip-tilt corrections of finite duration, resulting in:

- ✓ Finite Wavefront Measurement SNR → Residual rms error on both amplitude and phase for each beam and for each fiber (spatial white noise floor)
- ✓ Dynamic Wavefront Distortion between Successive Wavefront measurements and Corrections → low order spatial corrugations, primarily at telescope level

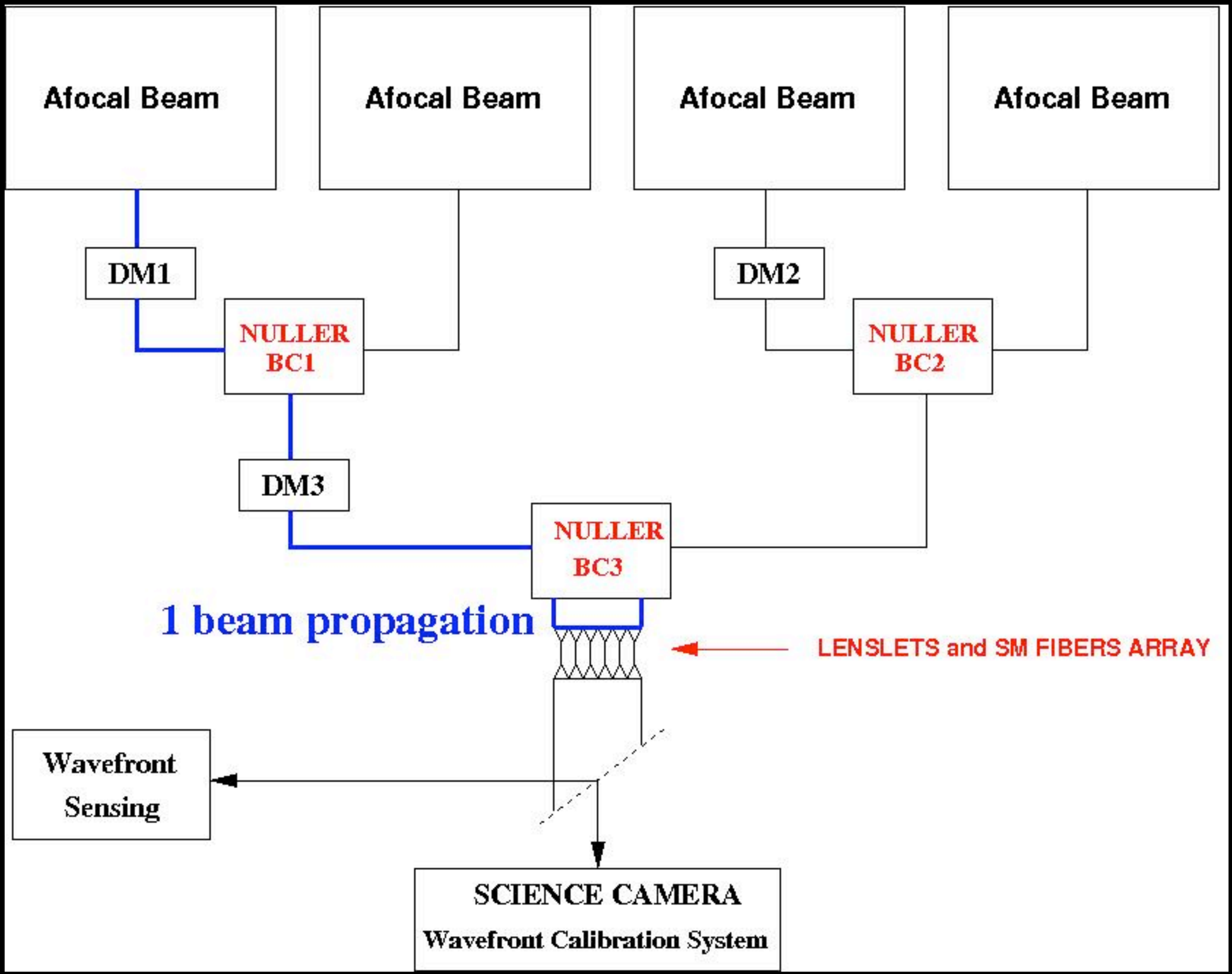
Simulations Principle and Building Blocks

Assumes science integration is made of many DM piston and tip-tilt corrections of finite duration, resulting in:

✓ Finite Wavefront Measurement SNR → Residual rms error on both amplitude and phase for each beam and for each fiber (spatial white noise floor)

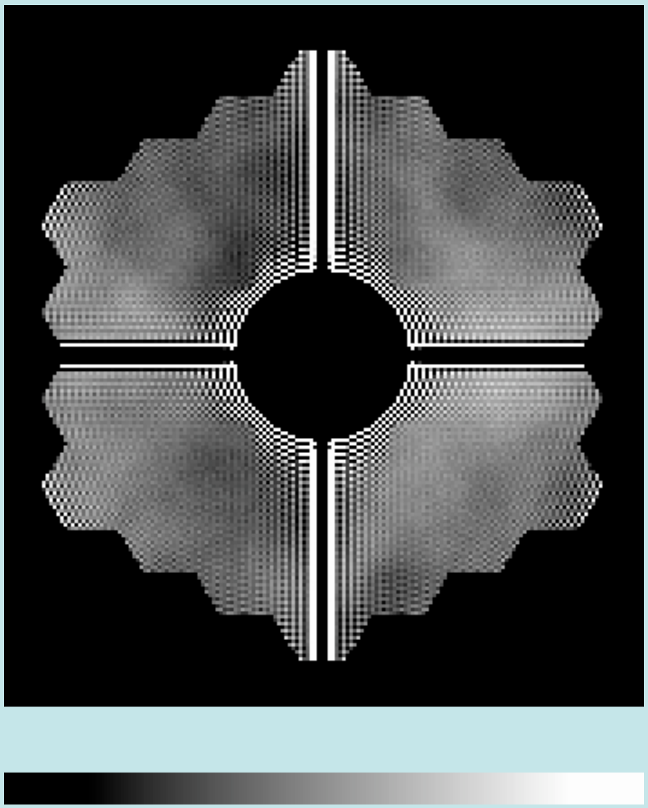
✓ Dynamic Wavefront Distortion between Successive Wavefront measurements and Corrections → low order spatial corrugations, primarily at telescope level

✓ Use “PROPER” Finite Diffraction Code to propagate individual beams (or telescopes) distortions to Fiber Lenslet Array


Afocal Beam
Afocal Beam
Afocal Beam
Afocal Beam
DM1
DM2
NULLER BC1
NULLER BC2
DM3
NULLER BC3
1 beam propagation
LENSLETS and SM FIBERS ARRAY
Wavefront Sensing
SCIENCE CAMERA
Wavefront Calibration System

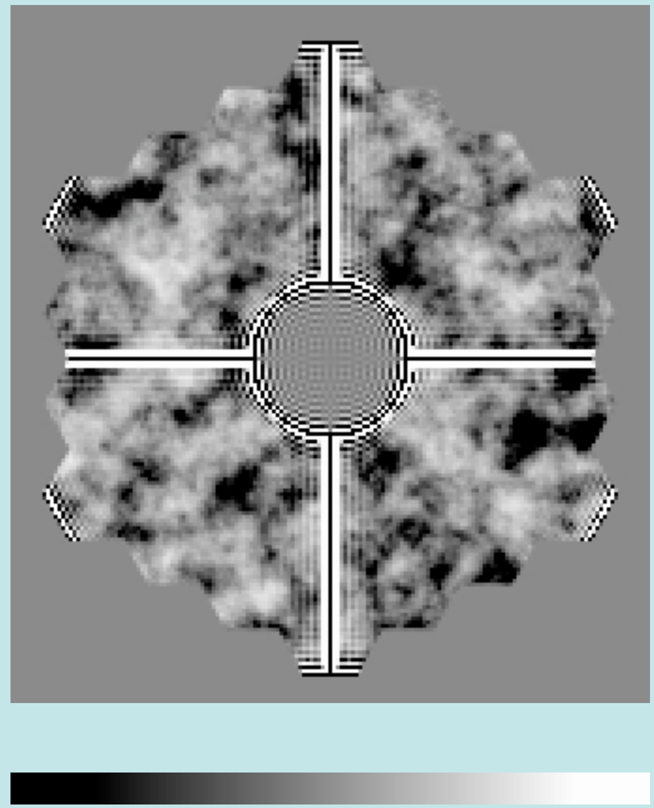
Individual Telescope (or Beam) Amplitude and Phase maps after propagation to 1st lenslets array

Amplitude Relative Fluctuations



-2×10^{-4} 2×10^{-4}

Phase (radians)



-2×10^{-4} 2×10^{-4}

Example: 5pm rms uncorrected surface error and 2×10^{-5} rms amplitude error (power law PSDs)

Simulations Principle and Building Blocks

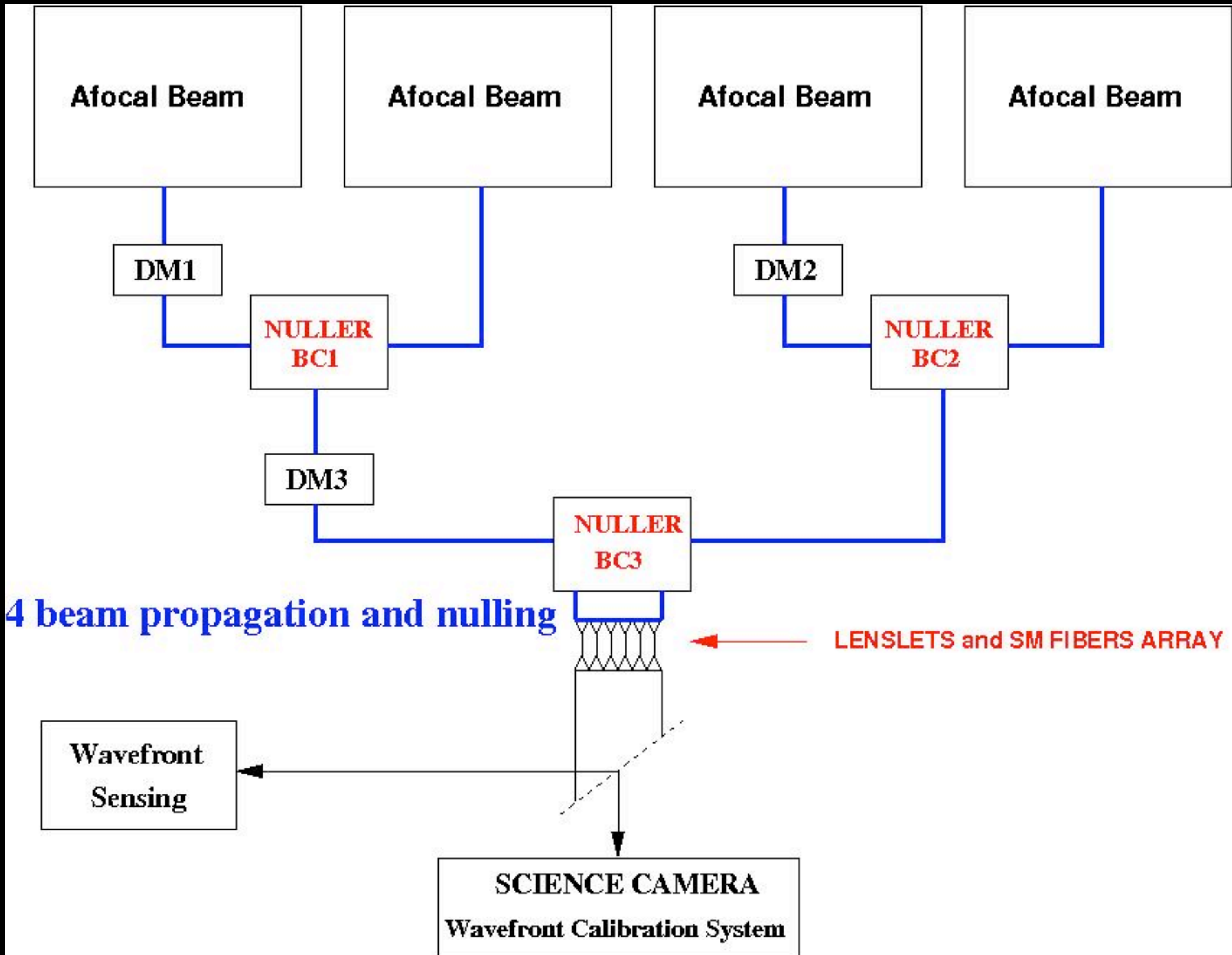
Assumes science integration is made of many DM piston and tip-tilt corrections of finite duration, resulting in:

✓ Finite Wavefront Measurement SNR → Residual rms error on both amplitude and phase for each beam and for each fiber (spatial white noise floor)

✓ Dynamic Wavefront Distortion between Successive Wavefront measurements and Corrections → low order spatial corrugations, primarily at telescope level

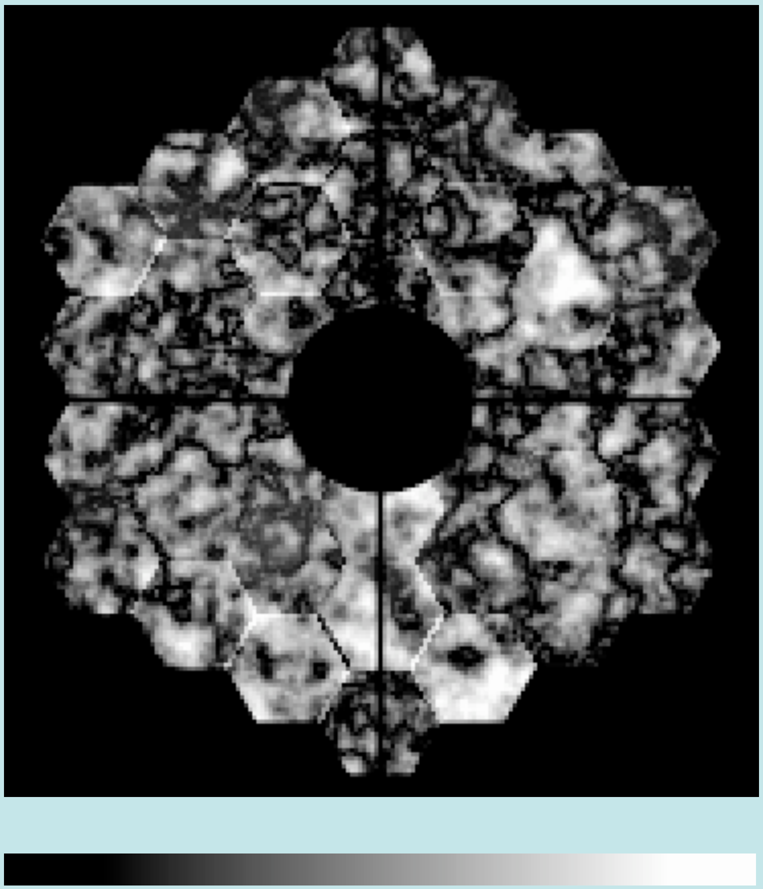
✓ Use "PROPER" Finite Diffraction Code to propagate individual beams ✓(or telescopes) distortions to Fiber Array

✓ Compute Nulled Field Amplitude and Phase Distribution before & after injection into each Single-Mode Fiber


Afocal Beam
Afocal Beam
Afocal Beam
Afocal Beam
DM1
DM2
NULLER BC1
NULLER BC2
DM3
NULLER BC3
4 beam propagation and nulling
LENSLETS and SM FIBERS ARRAY
Wavefront Sensing
SCIENCE CAMERA
Wavefront Calibration System

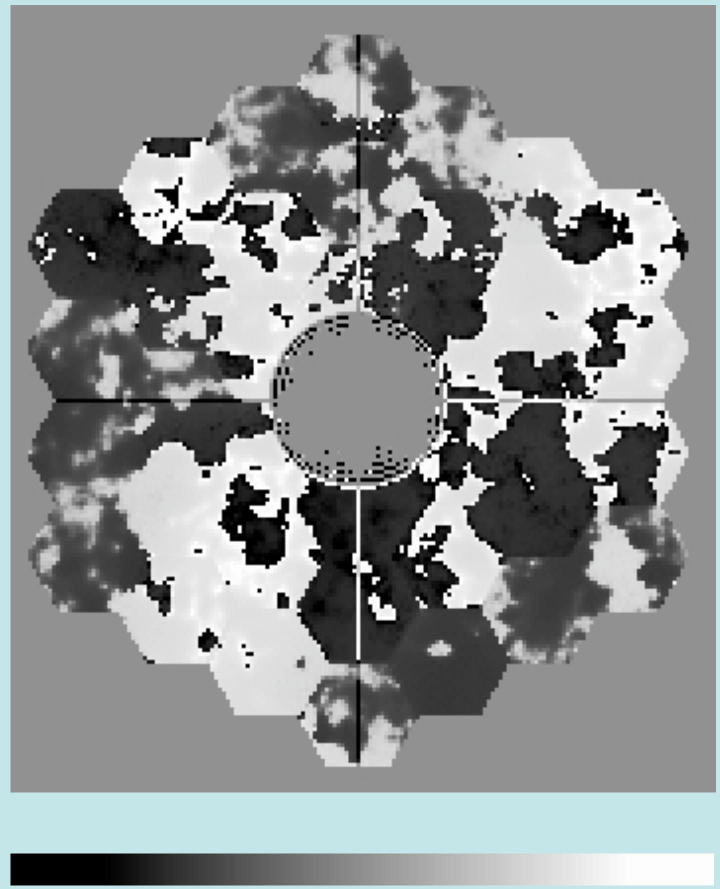
Nulled Electric Field Amplitude and Phase right after DM correction (before fibers):

Residual Amplitude

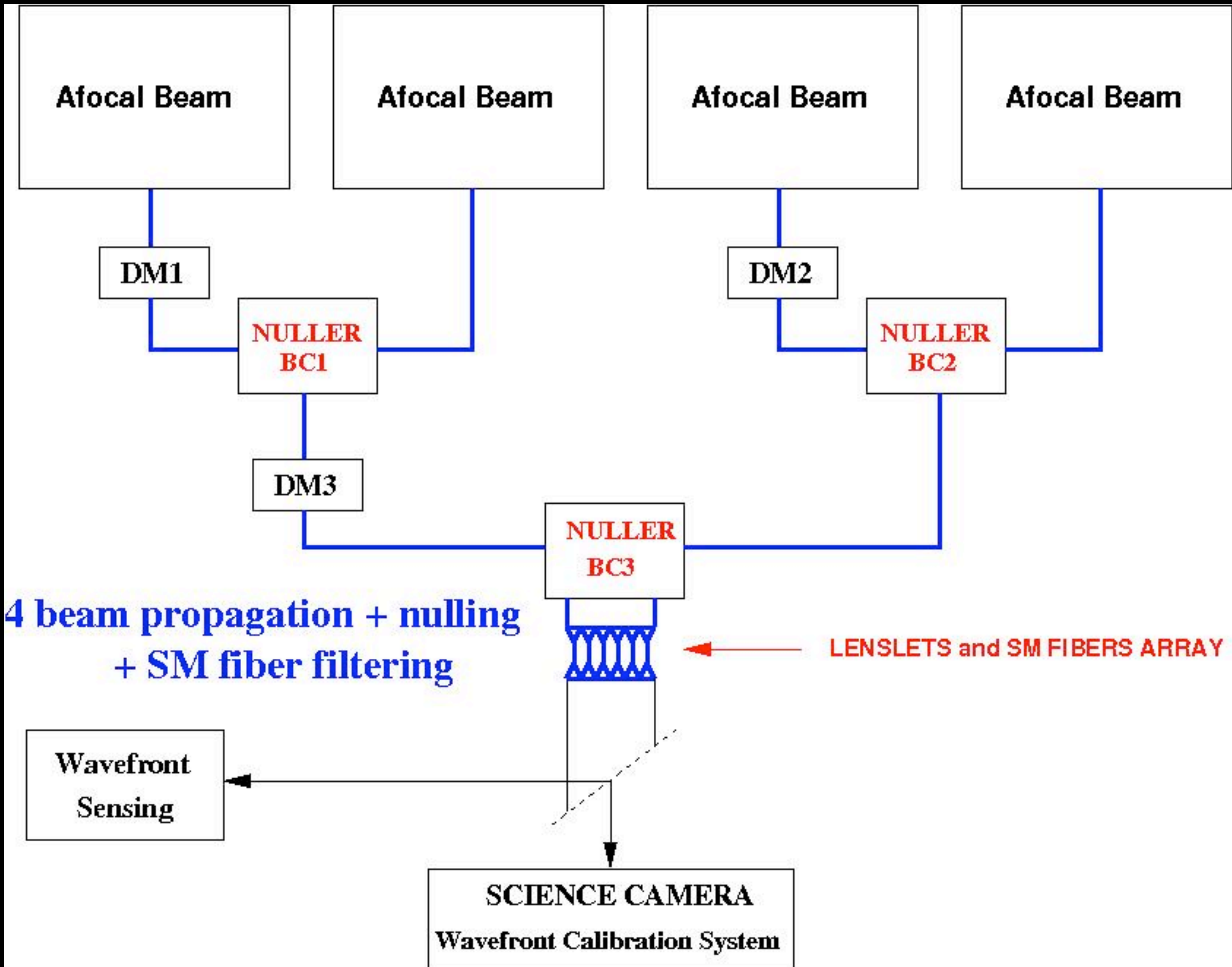


0 1.5 x 10^{-4} 3 x 10^{-4}

Phase (radians)



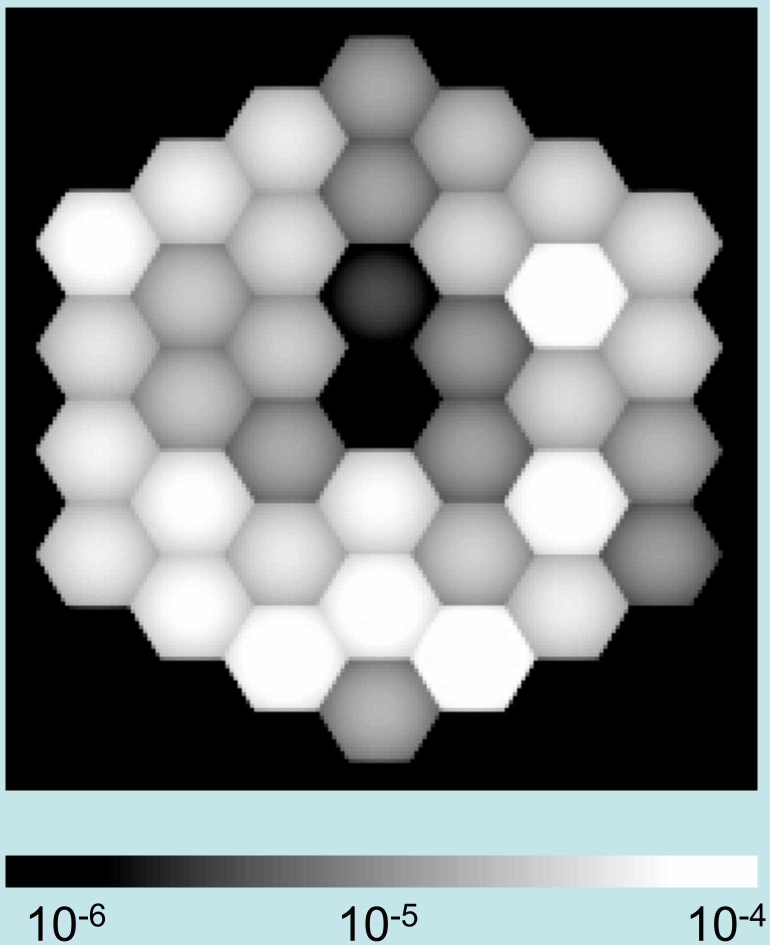
$-\pi$ π



Afocal Beam
Afocal Beam
Afocal Beam
Afocal Beam
DM1
DM2
NULLER BC1
NULLER BC2
DM3
NULLER BC3
4 beam propagation + nulling
+ SM fiber filtering
LENSLETS and SM FIBERS ARRAY
Wavefront Sensing
SCIENCE CAMERA
Wavefront Calibration System

Nulled Electric Field amplitude and phase after DM correction and SM fiber filtering

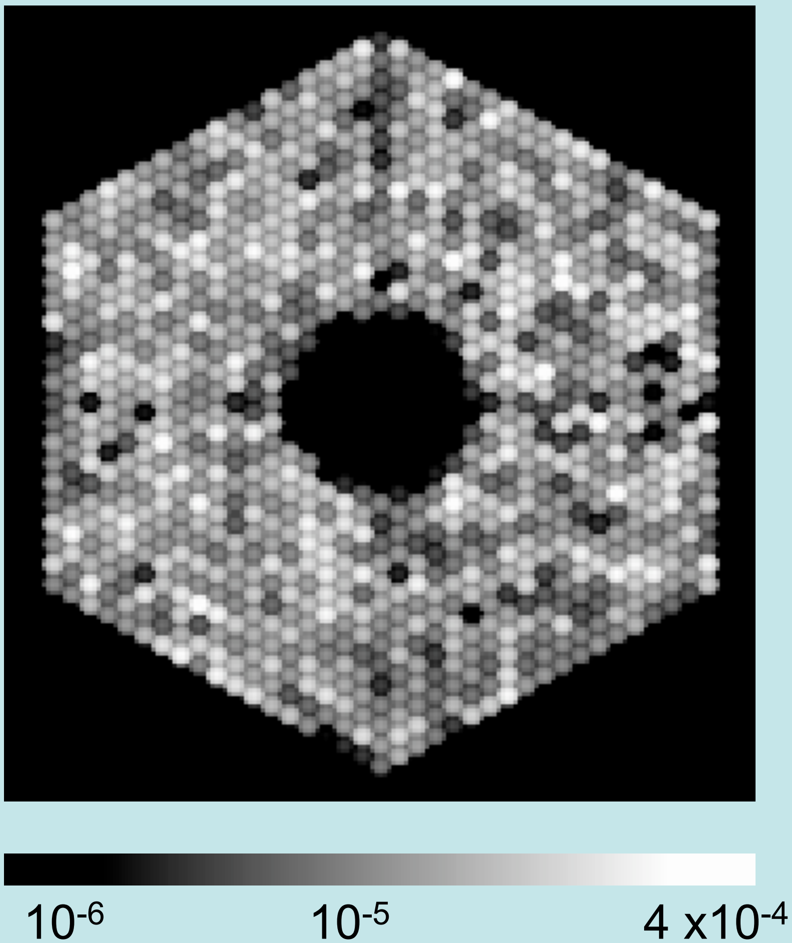
Residual Amplitude



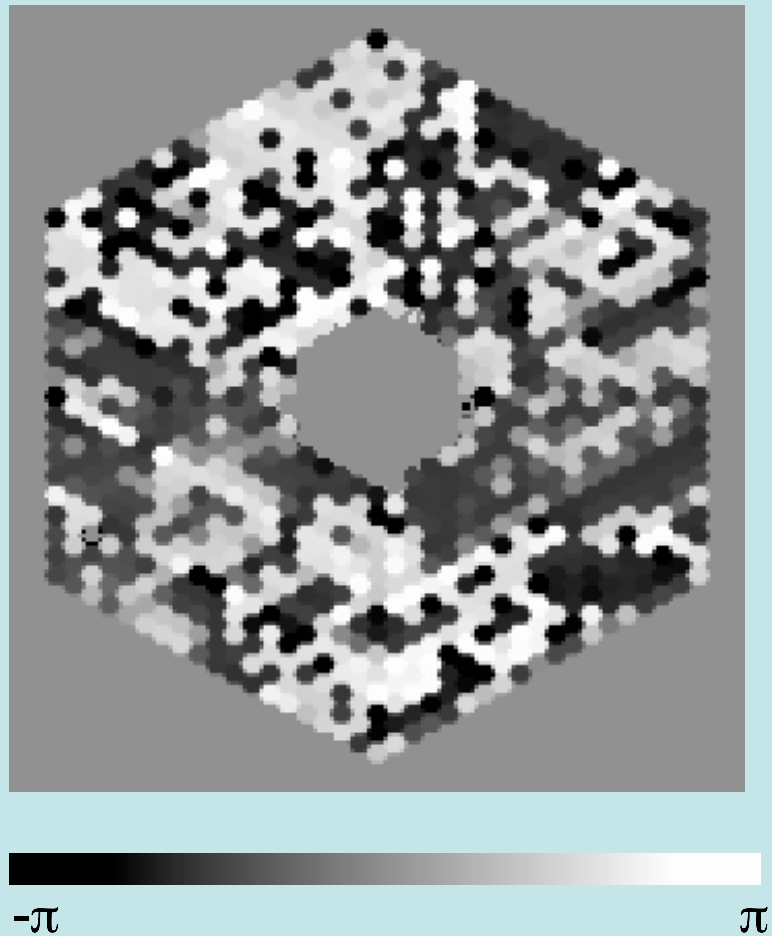
Phase (radians)

Nulled Electric Field amplitude and phase after DM correction and SM fiber filtering

Residual Amplitude



Phase (radians)



Simulations Principle and Building Blocks

Assumes science integration is made of many DM piston and tip-tilt corrections of finite duration, resulting in:

- ✓ Finite Wavefront Measurement SNR → Residual rms error on both amplitude and phase for each beam and for each fiber (spatial white noise floor)
- ✓ Dynamic Wavefront Distortion between Successive Wavefront measurements and Corrections → low order spatial corrugations, primarily at telescope level
- ✓ Use “PROPER” Finite Diffraction Code to propagate telescope distortions to Fiber Array
- ✓ Compute Nulled Field Amplitude and Phase Distribution after injection into each single-mode fiber
- ✓ Repeat for many wavelengths inside a given filter

Simulations Principle and Building Blocks

Assumes science integration is made of many DM piston and tip-tilt corrections of finite duration, resulting in:

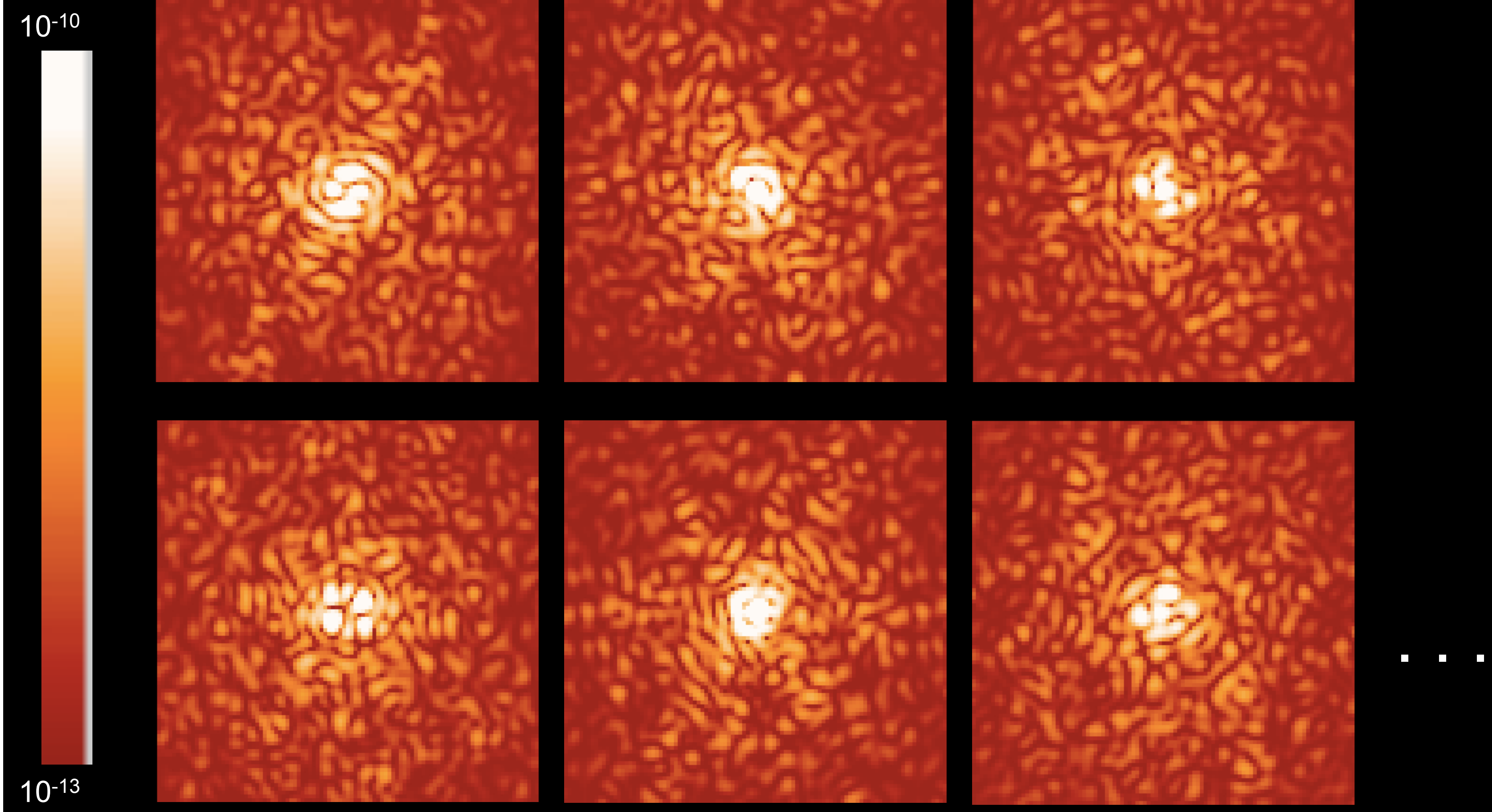
- ✓ Finite Wavefront Measurement SNR → Residual rms error on both amplitude and phase for each beam and for each fiber (spatial white noise floor)
- ✓ Dynamic Wavefront Distortion between Successive Wavefront measurements and Corrections → low order spatial corrugations, primarily at telescope level
- ✓ Use "PROPER" Finite Diffraction Code to propagate telescope distortions to Fiber Array
- ✓ Compute Nulled Field Amplitude and Phase Distribution after injection into each single-mode fiber
- ✓ Repeat for many wavelengths inside a given filter
- ✓ Repeat and Average over many instances

Simulations Parameters

- ✓ 11 wavelengths between 500 nm and 600 nm
- ✓ Segmented DM with 1027 hexagonal actuators (independent piston and tip-tilt controls for each)
- ✓ WFC error (due to Telescope Distortions in between WFC):
  - 0.10 mas rms tip-tilt per axis
  - 10pm total phase rms *per beam*, with power law PSD
  - 2 10^{-5} amplitude rms *per beam*, with power law PSD
- ✓ WF measurement error floor (induced by photon noise during WFS)
  - Residual opd= 10 pm rms *per beam* & per fiber.
  - Residual amplitude mismatch= 2 10^{-5} *per beam* & per fiber
- ✓ Physical Propagation (PROPER 1024^2 gridsize) to Lenslet Array in Pupil Plane
- ✓ Compute injection in each of 1027 fibers
- ✓ Repeat 10 times using temporal PSD per Zernike (white PSD assumed for now)

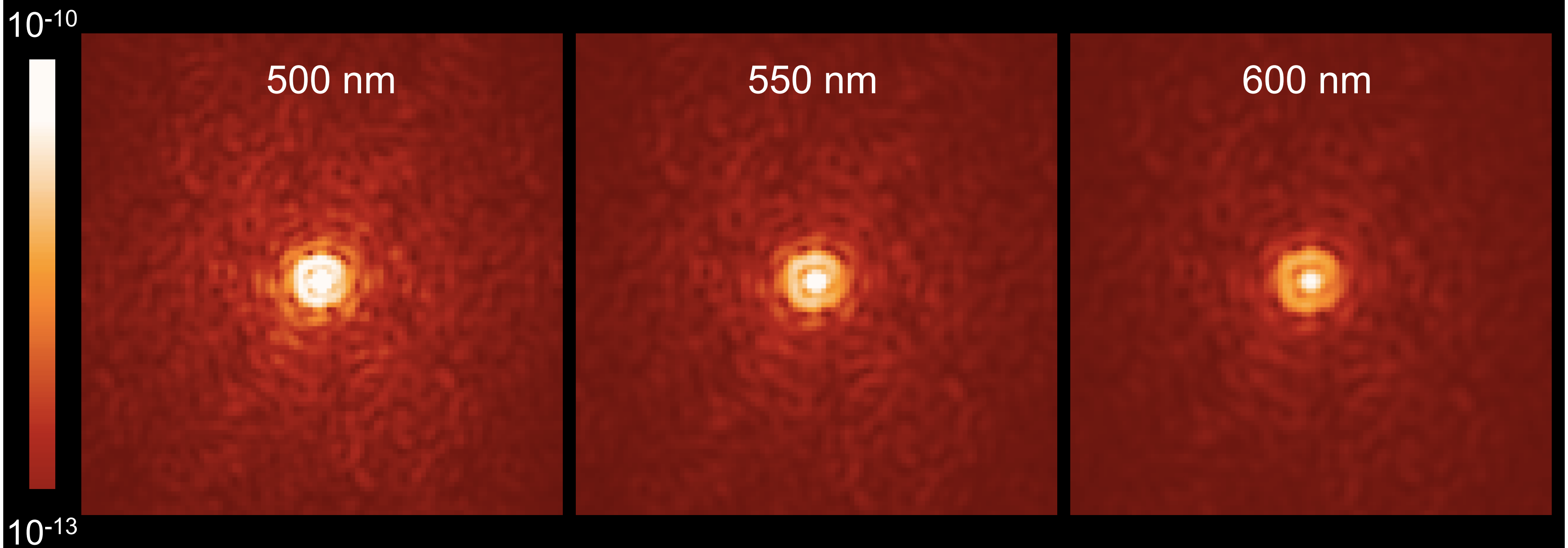
Single wavelength as a function of time

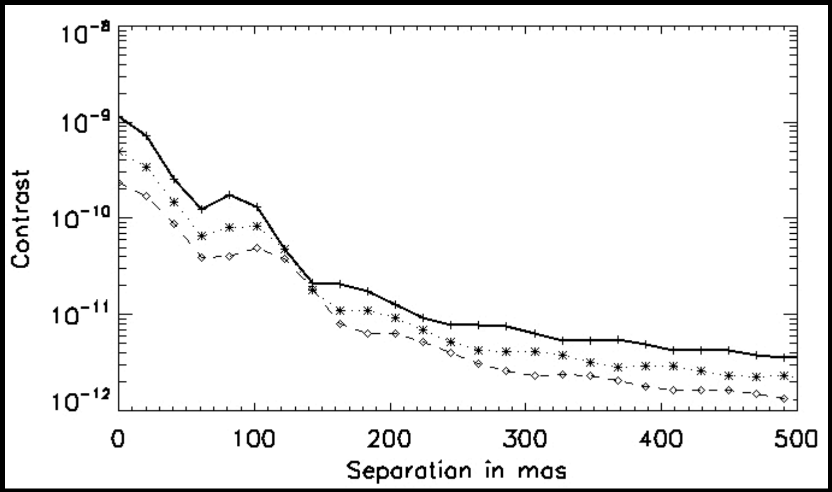
Speckle fields (central 2” x 2”) at 550 nm



Constrast vs Wavelength

2”x2 “ central speckle field (averaged over 10 instances):





Future Improvements to Fidelity

- ✓ Input realistic spatial/ temporal distortions at telescope level etc (from thermal/ mechanical modeling)
- ✓ Include realistic input from WFC/WFS systems
- ✓ Include Nulling BC Chromatic effects (also coupled to OPD fluctuations)
- ✓ Include all optical surfaces
- ✓ Include polarization effects
- ✓ Simulate SM fiber / lenslet array imperfections (presently assumed perfect but for $\lambda/25$ rms fiber length rms)
- ✓ Include stellar finite size

Current Status

✓ Main Simulation “building blocks” are in:

- Physical Optics Propagation (PROPER) from entrance aperture to final focal plane (uses angular spectrum and/or Fresnel approximation)

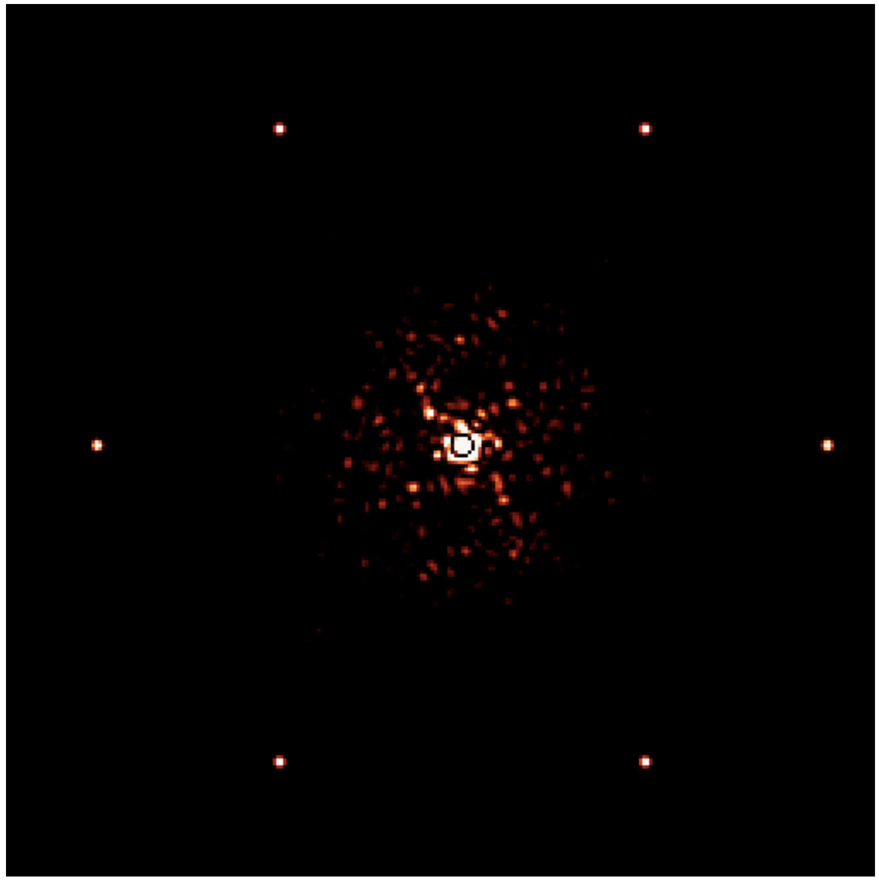
- Computes SM fibers injection (both amplitude and phase effects)

- Folds in residual spatial and temporal wavefront distortions, specifying their PSDs (ad-hoc for now, should come from more realistic inputs in terms of perturbations, WFS and WFC performance)

✓ Can be used to provide top-level requirements in terms of phase and amplitude stability (WFC/WFS specs)

Back-up Slides

Replicas due to stepwise wavefront



With 1027 fibers and a 2m diameter sub-beams, replicas are farther than 1” in the visible